A remote-sensing and modeling perspective of ice crystals in deep convective clouds

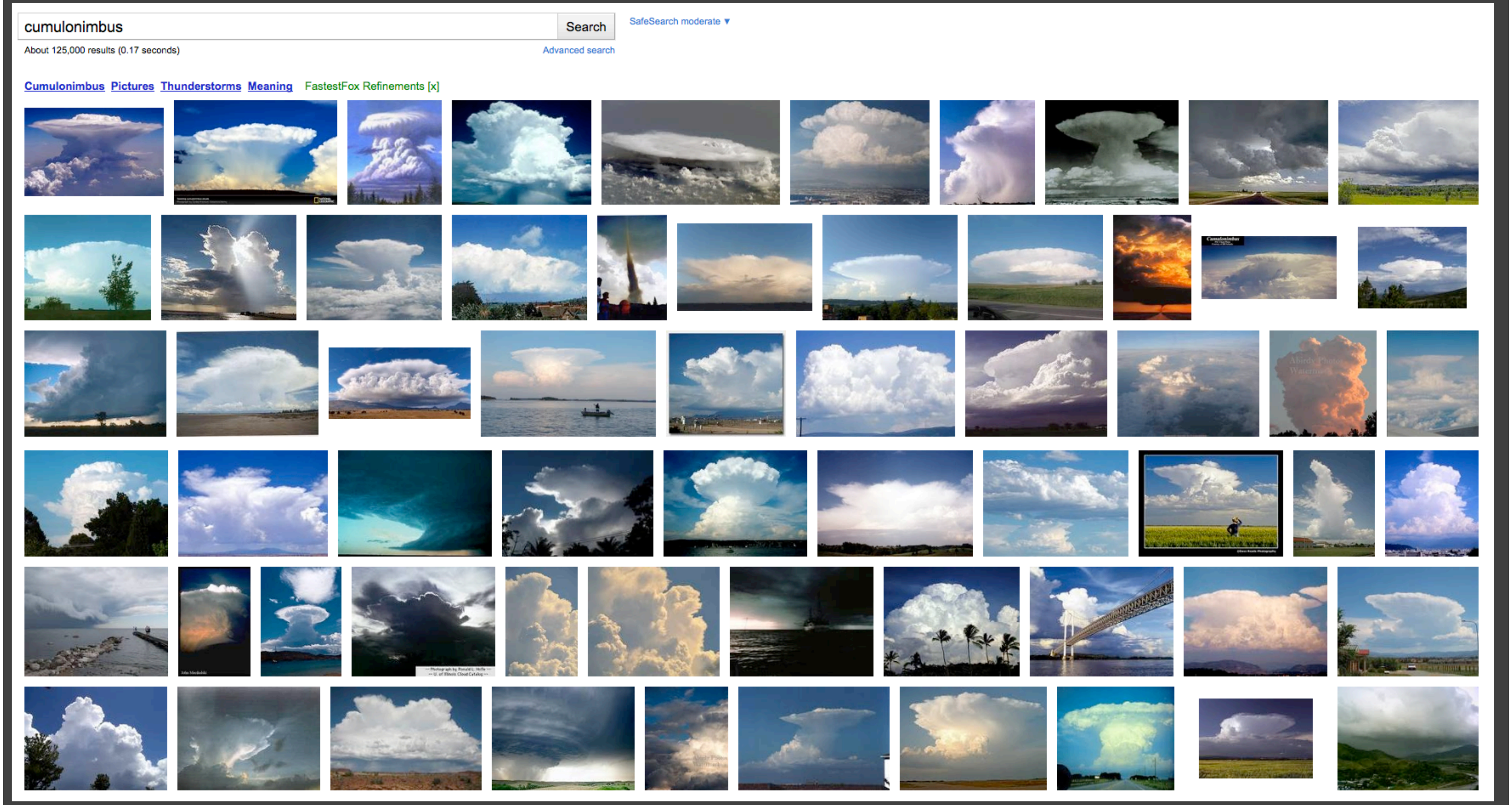
Bastiaan van Diedenhoven

(GISS lunch seminar)

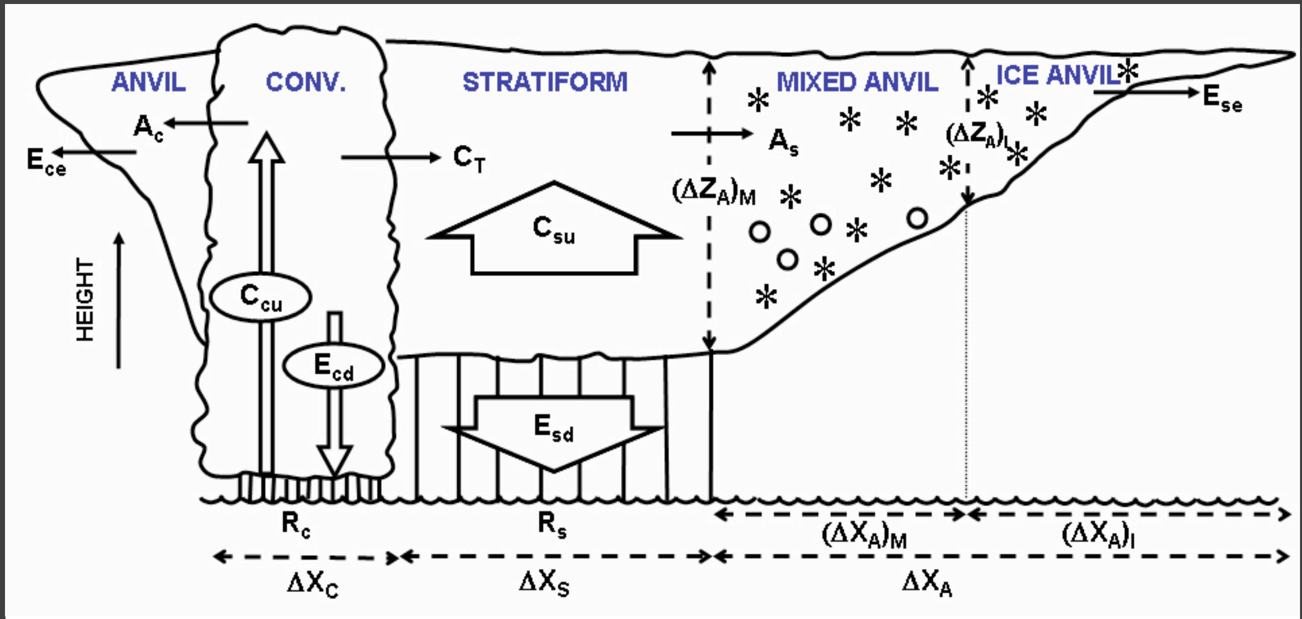
Ann Fridlind & Andrew Ackerman

25/5/11

Deep convective clouds



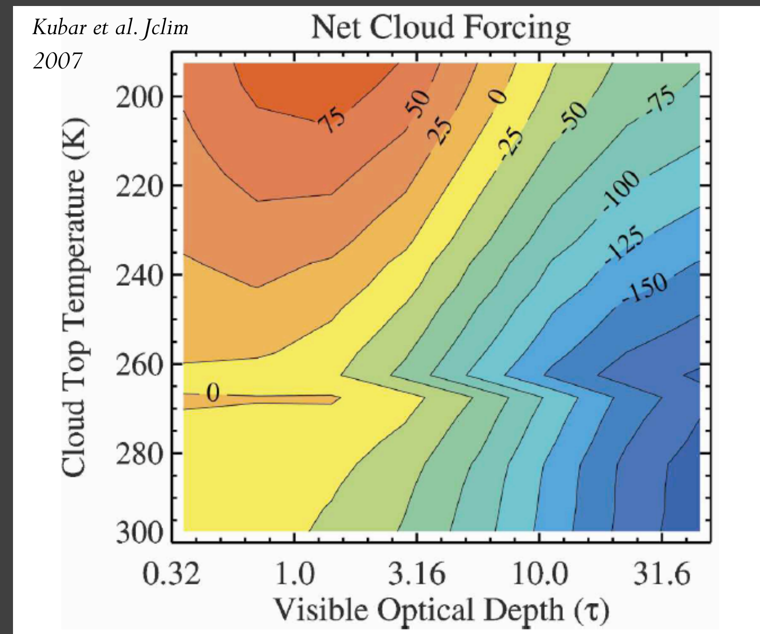
Deep convective clouds



Adapted from Houze et al. (1980)

Net Forcing

- Shortwave/longwave cloud forcing depends on
  - Cloud top temperature
  - Optical thickness
  - Ice crystal sizes
  - Ice crystal shapes ('Habits')
  - Glaciation temperatures
  - ….



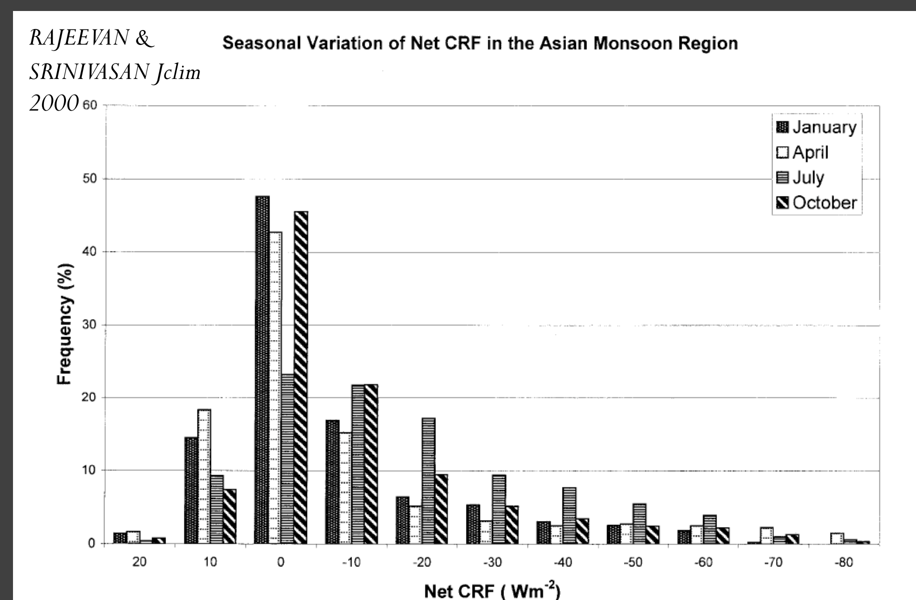
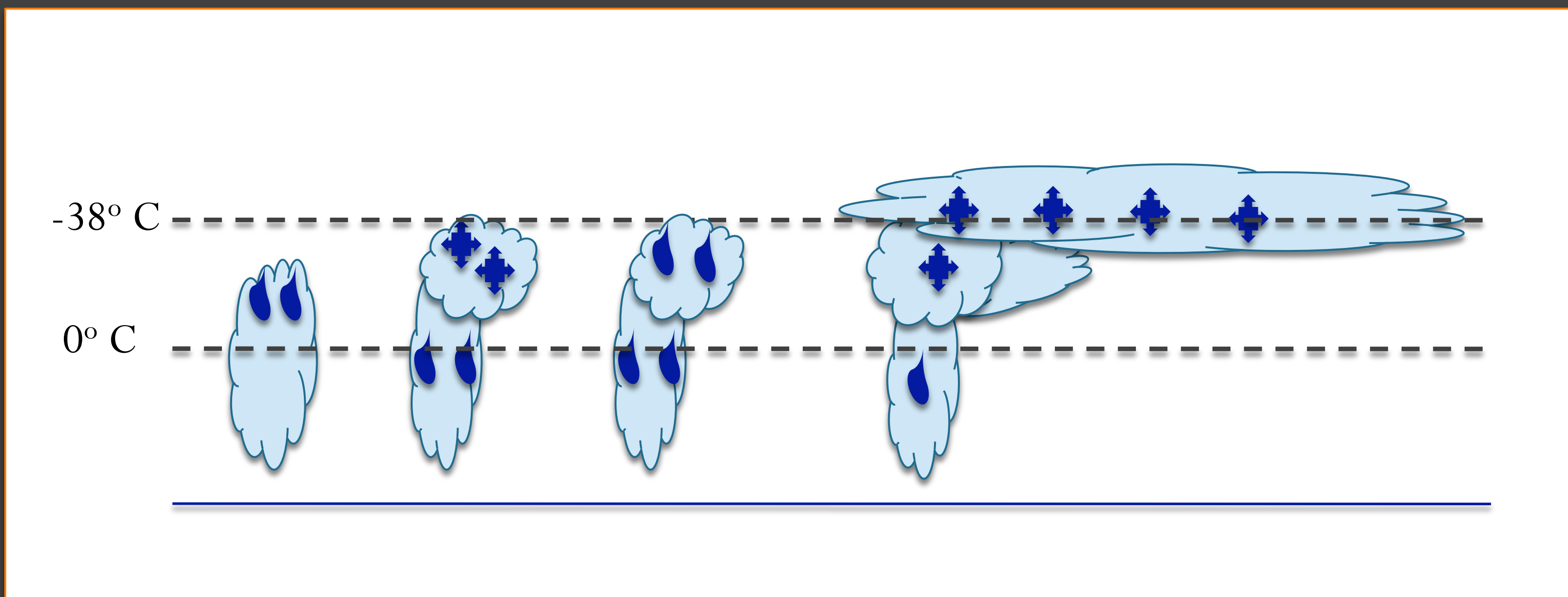


FIG. 2. Frequency distribution (in percentage) of ERBE net cloud radiative forcing for 10 W m^{-2} interval for Jan, Apr, Jul, and Oct. Period: 1985–88. Region: 0°–30°N, 60°–120°E.

Ice formation in deep convective clouds

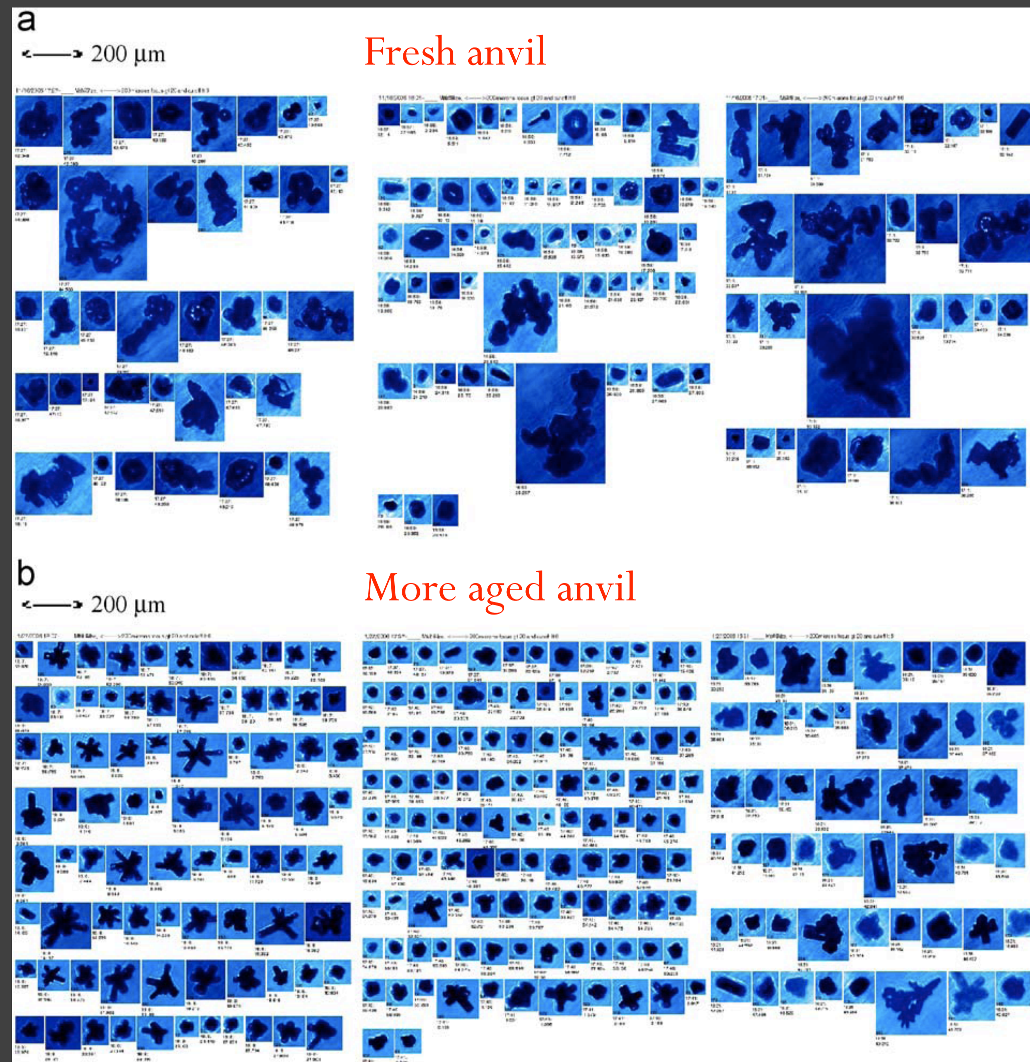
- Homogeneous ice formation
  - Direct freezing of droplets
  - T < -38 C
- Heterogeneous ice formation
  - Ice formation induced by ice nuclei (IN)
  - 0? C > T >-38 C



Ice crystals in Tropical deep convection

From Baran, review, JQSRT 2009

- CPI images
  - Many irregular shapes
  - Some more ‘pristine’ rosettes in aged anvil



Objectives

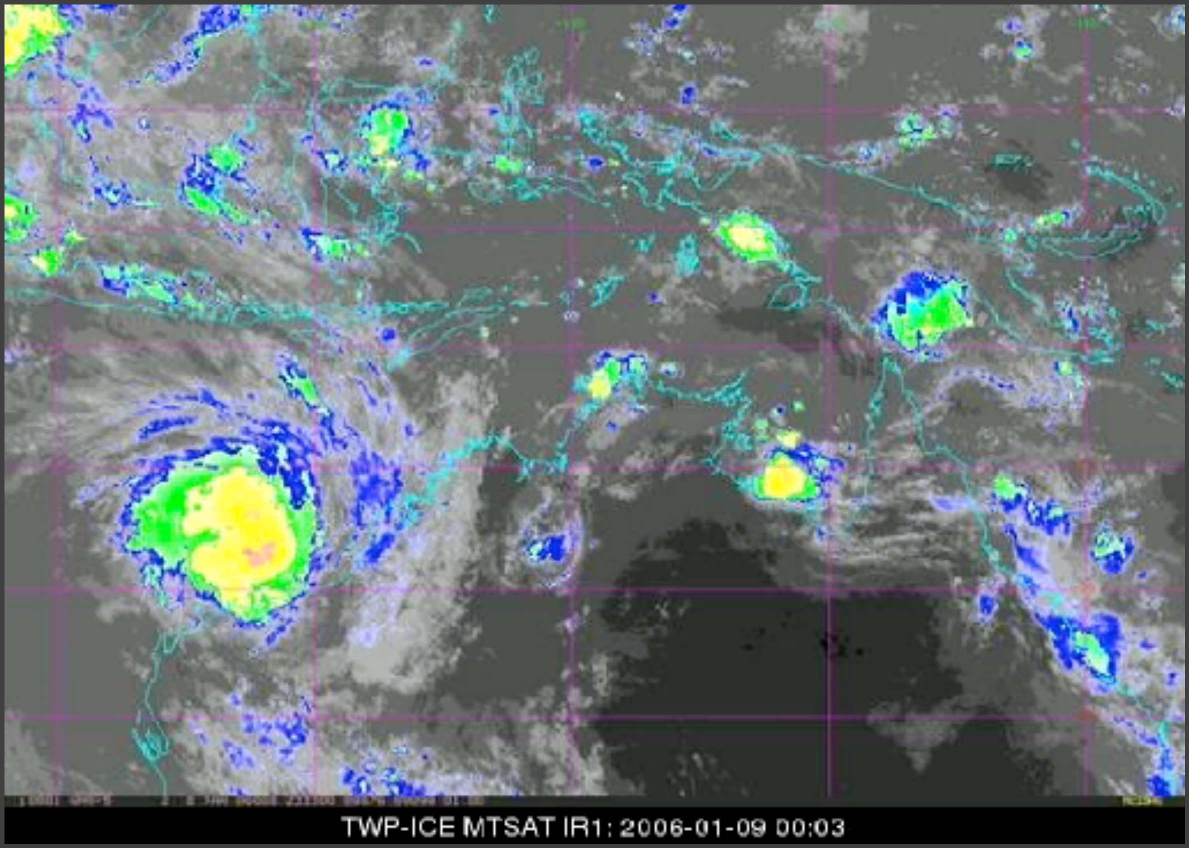
- Ice formation not well understood
- Use cloud-resolving modeling studies to investigate
  - Ice formation processes
  - Sensitivity to IN and CCN concentrations
- Provide observational constraints on
  - Glaciation temperatures
  - Ice crystal sizes
  - Ice crystal shapes ('Habits')

ARM's TWP-ICE campaign

- The Tropical Warm Pool—International Cloud Experiment
- Near Darwin, Australia
- From January 20 through February 13, 2006
  - Active monsoon 20-24 Jan.
  - Suppressed 25 Jan – 3 Feb.
  - Monsoon break >3 Feb.
- Over ocean, weak daily cycle

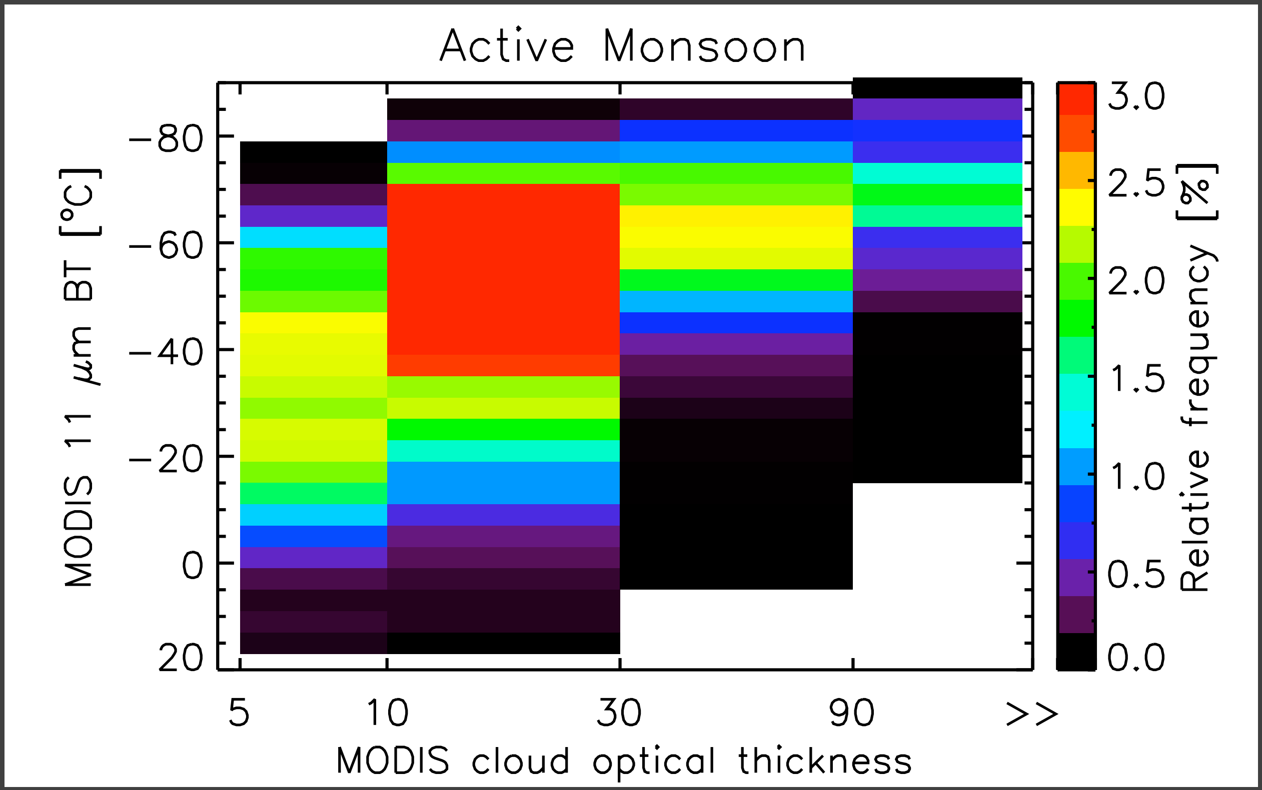
Geostationary MTSAT IR measurements

- Active monsoon 16-24 Jan.
- Suppressed 25 Jan – 3 Feb.
- Monsoon break >3 Feb.



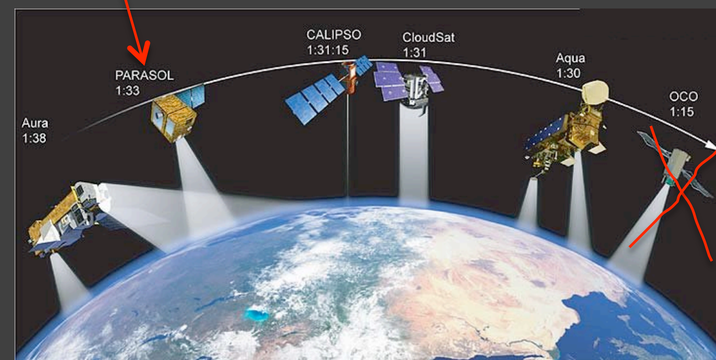
MODIS brightness temperature and optical thickness

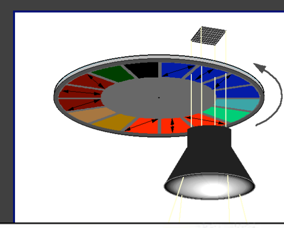
- Within 5° from Darwin
- Over sea
- Active Monsoon

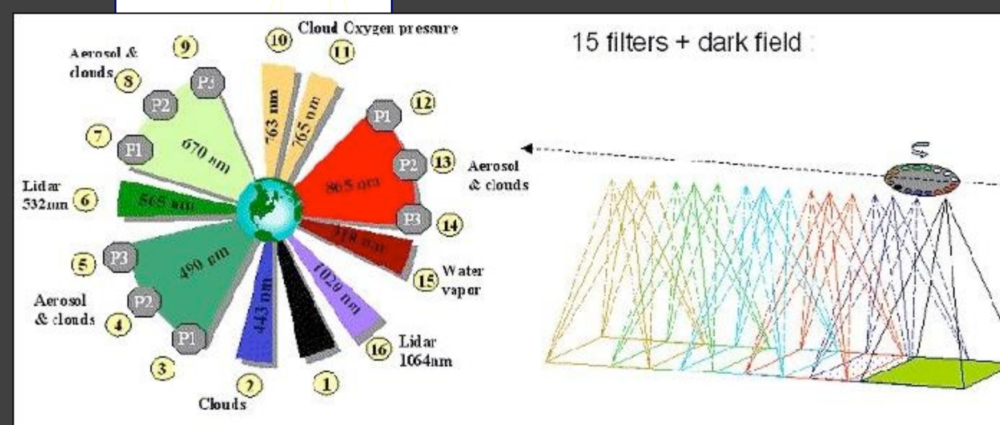


Cloud phase information from POLDER-PARASOL

- Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar
- Was in A-train (2004-2009 ran out of fuel)
- 10 x 10 km^2 resolution
- Provides reflectivity at 9 wavelengths at 13-15 viewing angles
- Polarized reflection at 490, 670 & 865 nm







Polarized reflectance

- Polder measures Stokes parameters I, Q & U
- Polarized reflectance

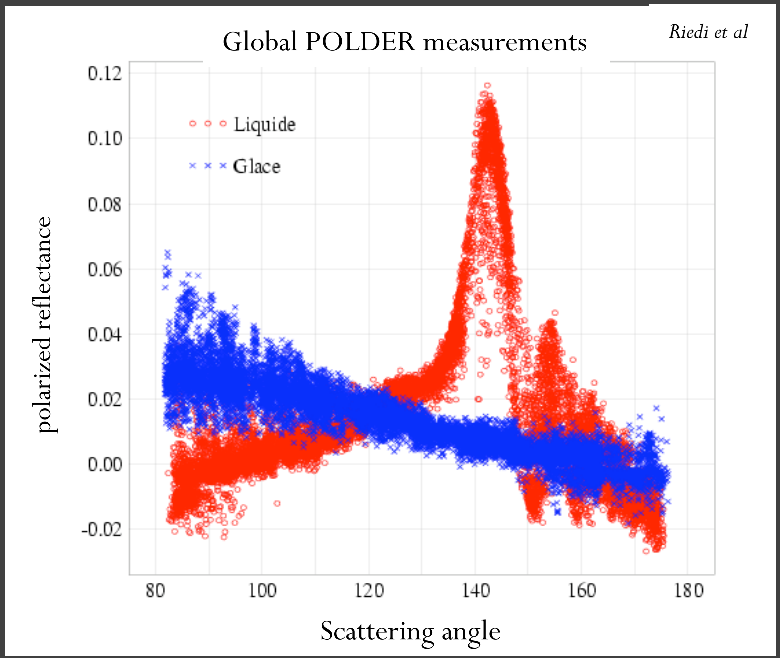
$$R_p(\mu) = \frac{\pi\sqrt{Q(\mu)^2 + U(\mu)^2}}{\mu_0 F_\odot},$$

(F_0 is incoming Solar, μ_0 is cosine of solar zenith angle)

  - Dominated by low order scattering
  - Saturated for cloud optical thickness > ~2
  - Probes cloud top

Cloud phase information from POLDER-PARASOL

- Directional polarized reflectance (R_p)
- Phase retrieval
  - Droplets show rainbow feature in R_p at 140 degrees
  - No/weak structure in Rp due to ice



POLDER Liquid index

- Fit straight line through 120°-160° measurements
- Ice index = Mean(|fit-measurement|)
- Straight-forward to simulate from model

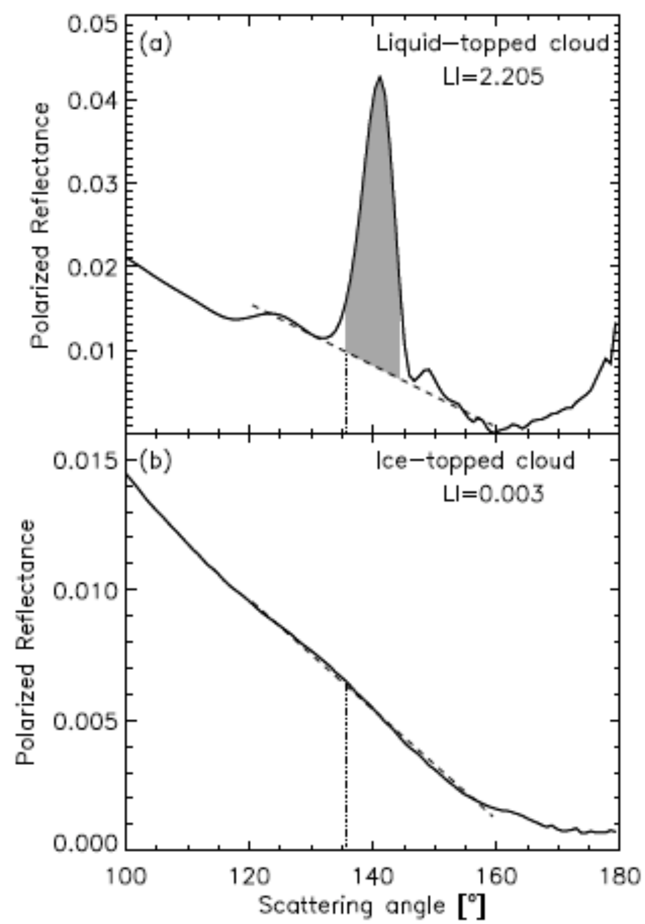
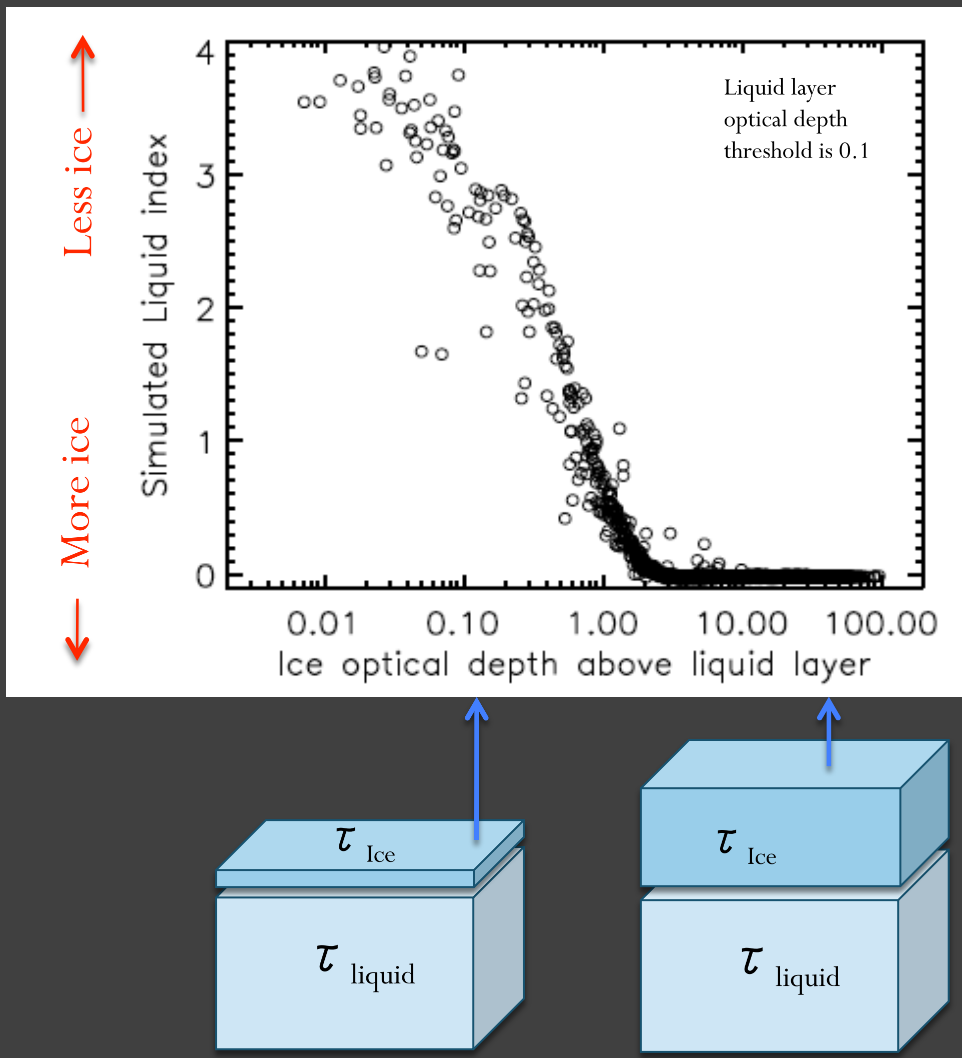


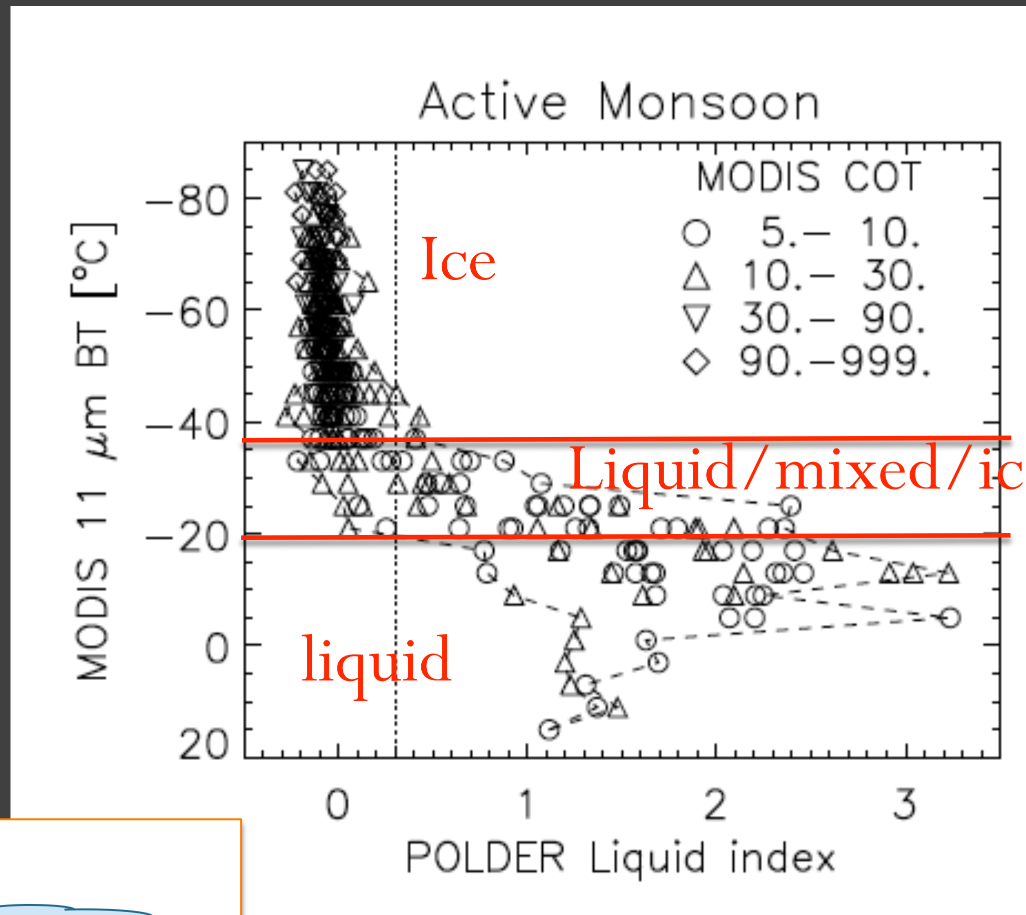
FIG. 2. Illustration of the definition of the liquid index (LI) for an liquid-topped cloud (a) and ice-topped cloud (b). See text for explanation.

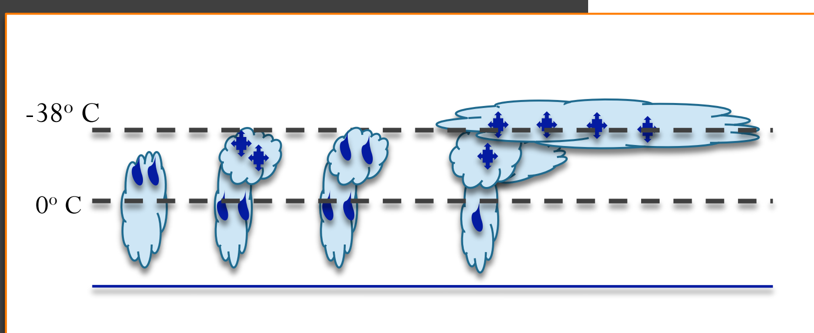
Physical interpretation of liquid index

- Liquid index
  - Indicates to what degree liquid is *obscured* by ice above
  - ~3 for pure water clouds
  - ~0 for pure ice clouds or ice *topped* clouds



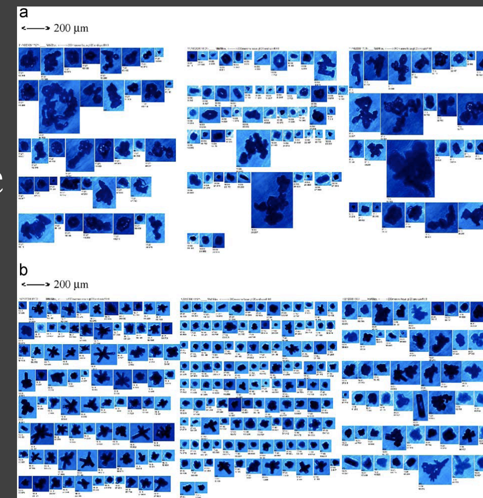
Liquid index for TWP-ICE active monsoon





Ice shape information from POLDER-PARASOL

- Polarized reflectance depends on ice shape
- Most important parameters are:
  - Aspect ratio of ice crystal (components)
  - Small-scale roughness



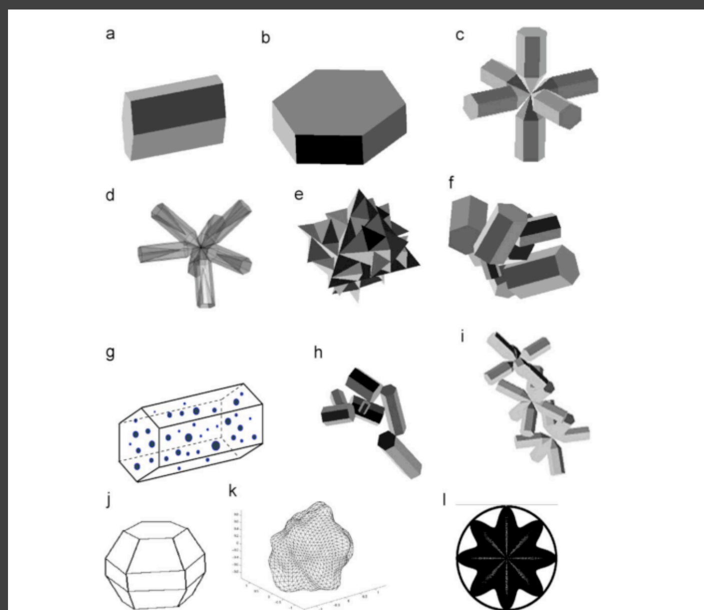
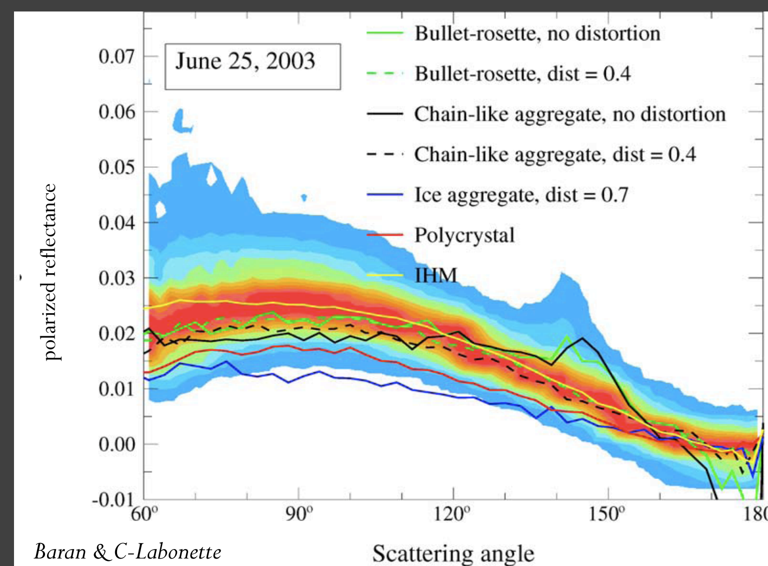
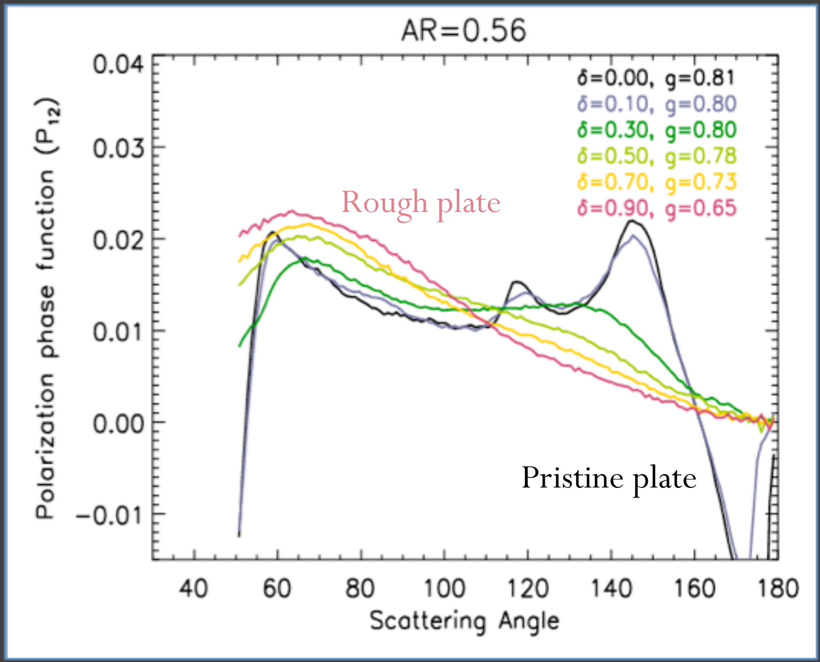


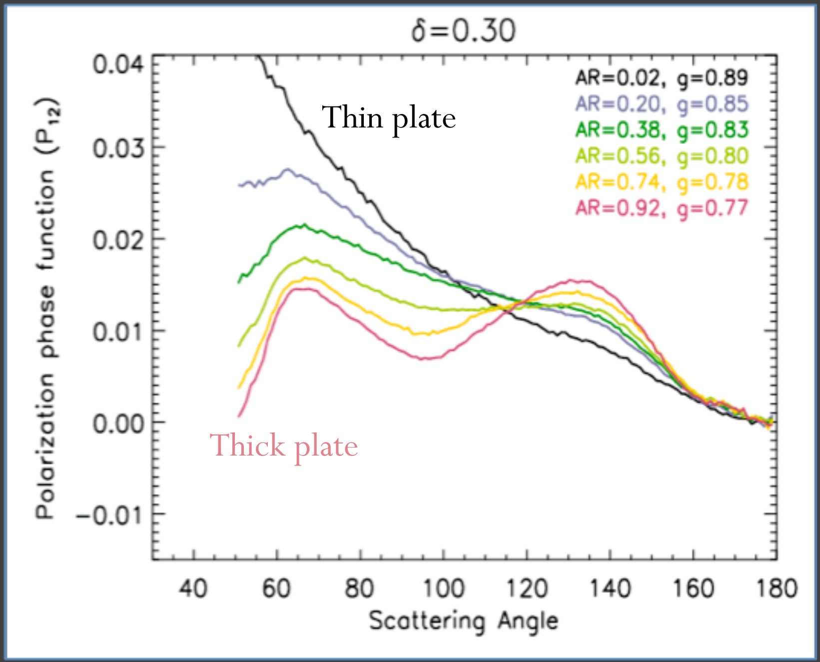
Fig. 3. Single ice crystal models used to predict the light scattering properties of cirrus: (a) the pristine hexagonal column, (b) the pristine hexagonal plate, (c) the six-branched bullet-rosette, (d) the six-branched bullet-rosette with conical air cavities within each branch, (e) the polycrystal, (f) the hexagonal ice aggregate, (g) the Inhomogeneous Hexagonal Monocrystal, (h) the hexagonal chain aggregate, (i) the rosette-aggregate, (j) the droxtal, (k) the Gaussian random sphere and (l) the Chebyshev polynomial.



Polarized phase function

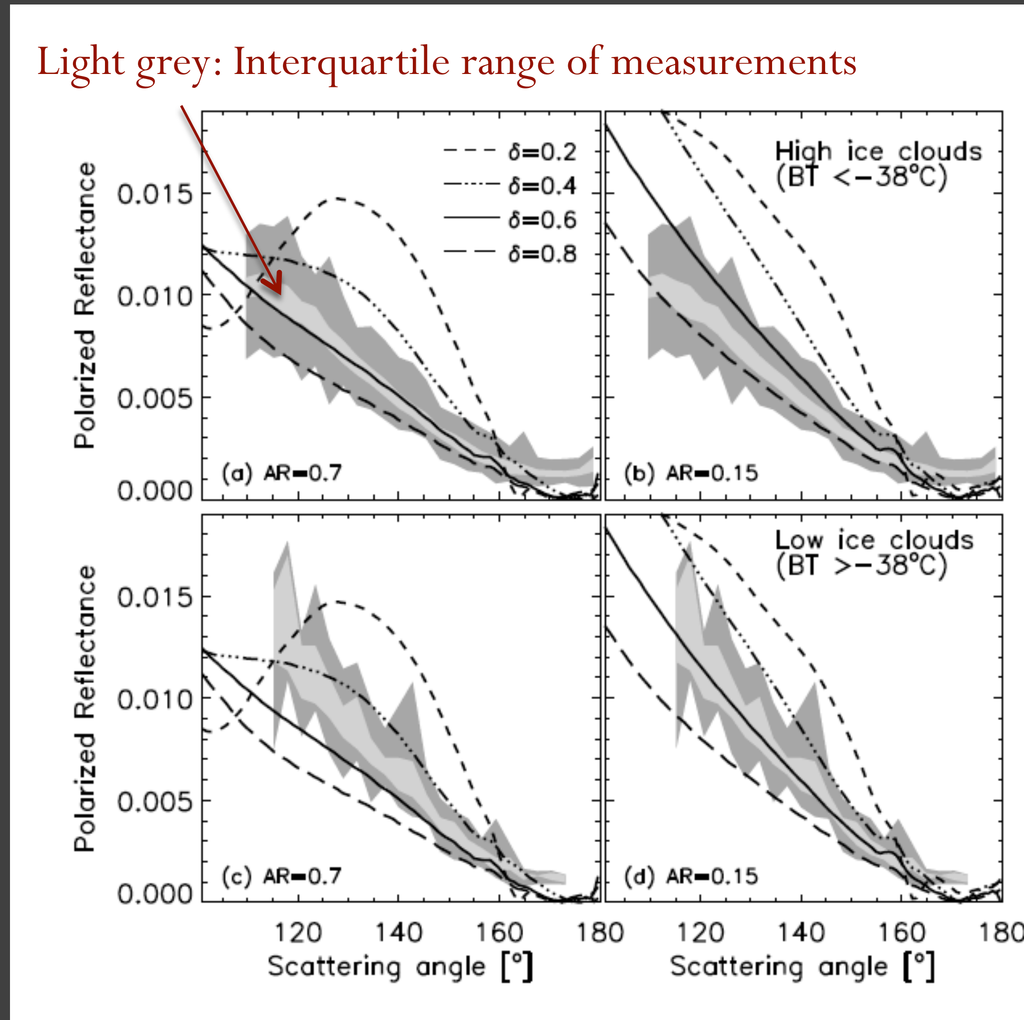
- Structures decrease with increasing roughness
- Scattering <120º increases with increasingly extreme aspect ratio





Ice shape information from POLDER-PARASOL

- Severely roughened ice
- Compact AR~0.7 crystals in cold clouds (homogeneous ice formation?)
- More extreme AR in warmer clouds (heterogeneous ice formation?)

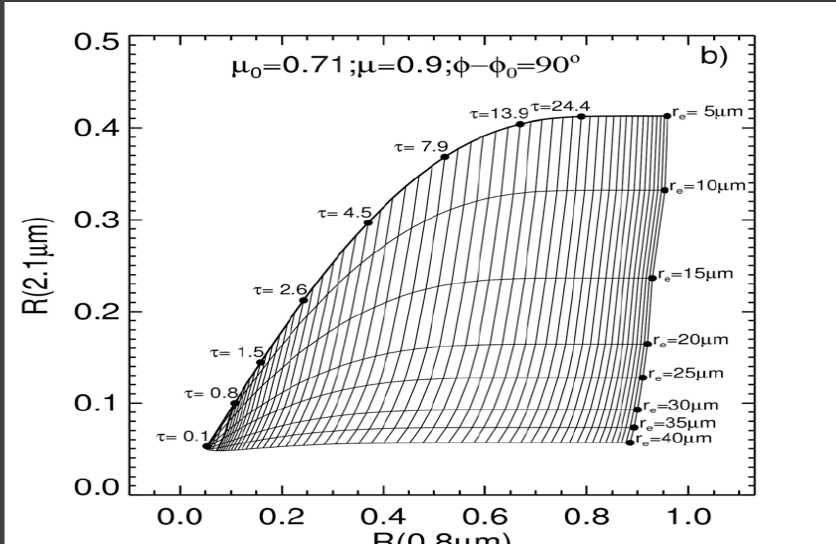


MODIS Aqua ice crystal effective radius and cloud optical thickness

$$R_{eff} = \frac{3}{4}\frac{\int_0^\infty V(D)N(D)\,dD}{\int_0^\infty A_p(D)N(D)\,dD},$$

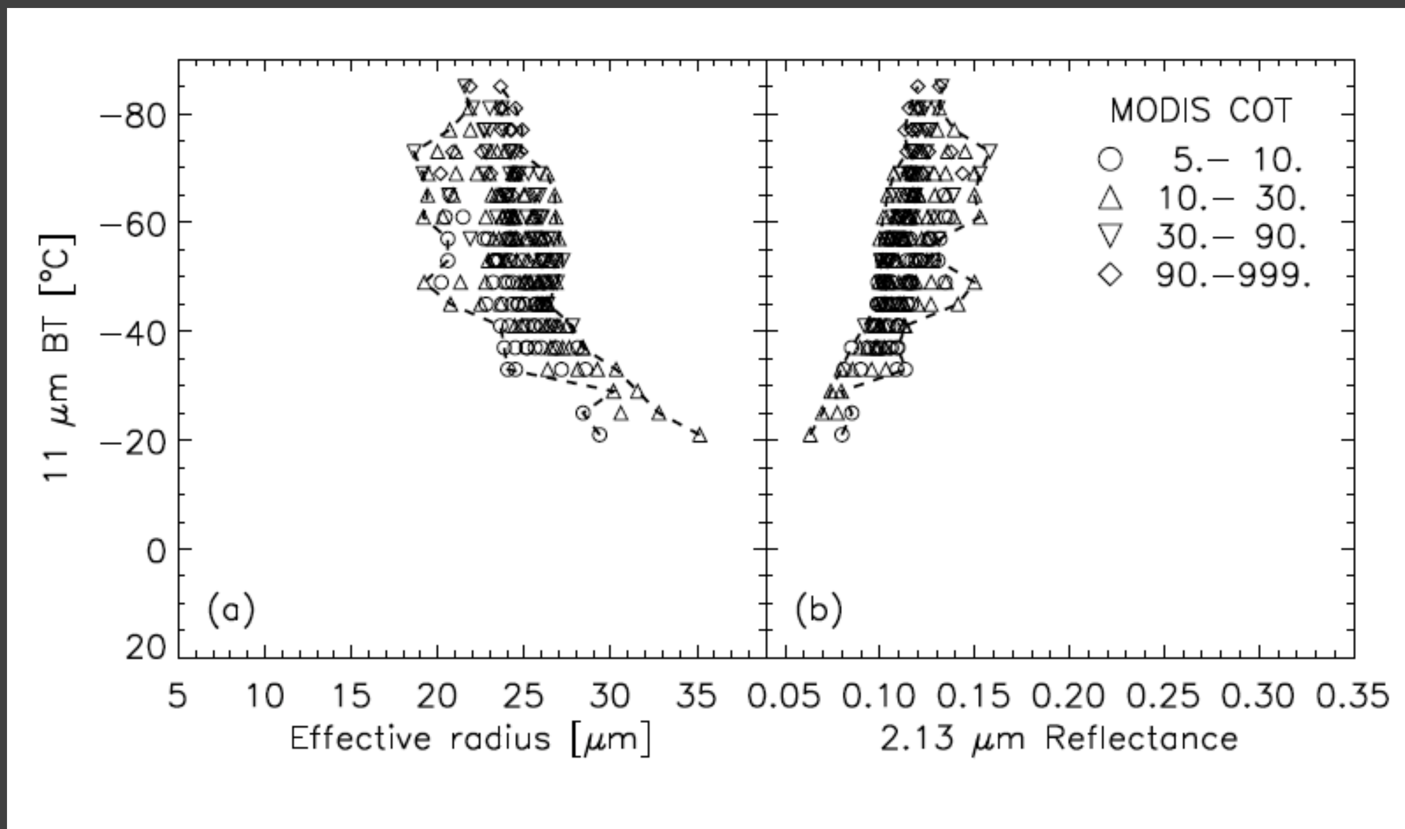
- Ice crystal effective radius
- cloud optical thickness

from 0.87 μm (non-absorbing)
and 2.13 μm (absorbing)



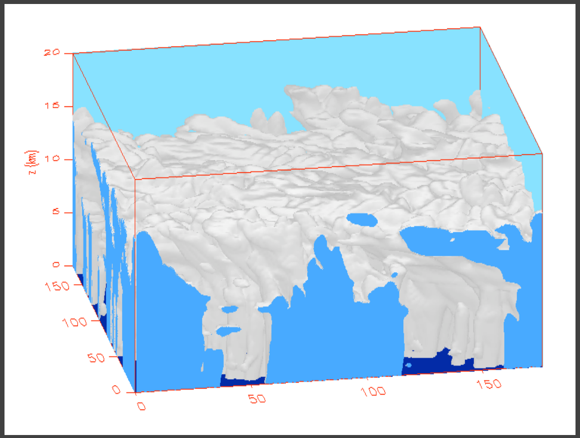
Zhang et al. 2010

MODIS ice effective radius and 2.13 um reflectance



DHARMA CRM Simulations

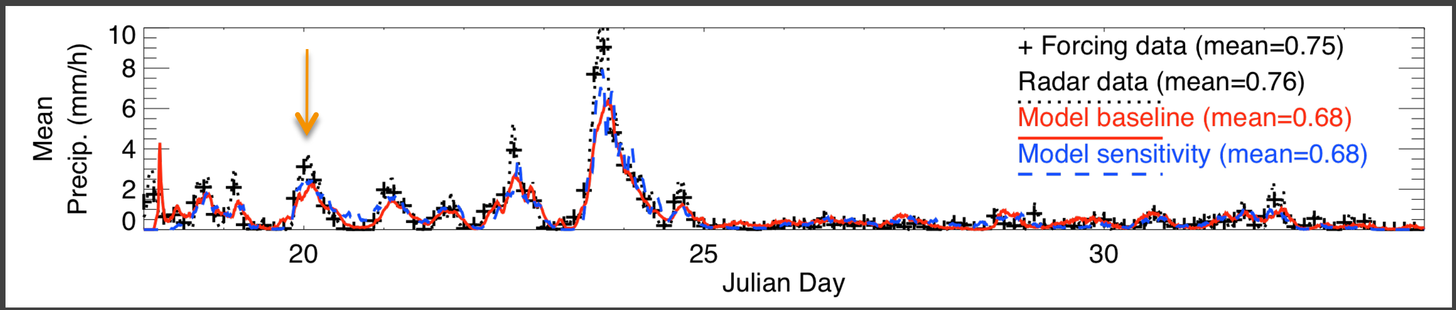
(Ackerman et al., *Nature* 2004; Fridlind et al, *JGR* 2007)



- Grid
  - $176 \times 176 \times 20$ km^3 domain
  - $192 \times 192 \times 96$ grid points (for now)
- Microphysics
  - Size resolved microphysics in 36 bins
  - Fluffy aggregates and dense graupel ice types
  - Ice properties modeled using (Böhm et al., *Atm. Res.* 1992)
    - Mass-Diameter relationships (Mitchell, *JAS*, 1996)
    - Area-Diameter relationships (Mitchell, *JAS*, 1996)
    - Aspect ratios (Korolev & Isaac, *JAS*, 2003)

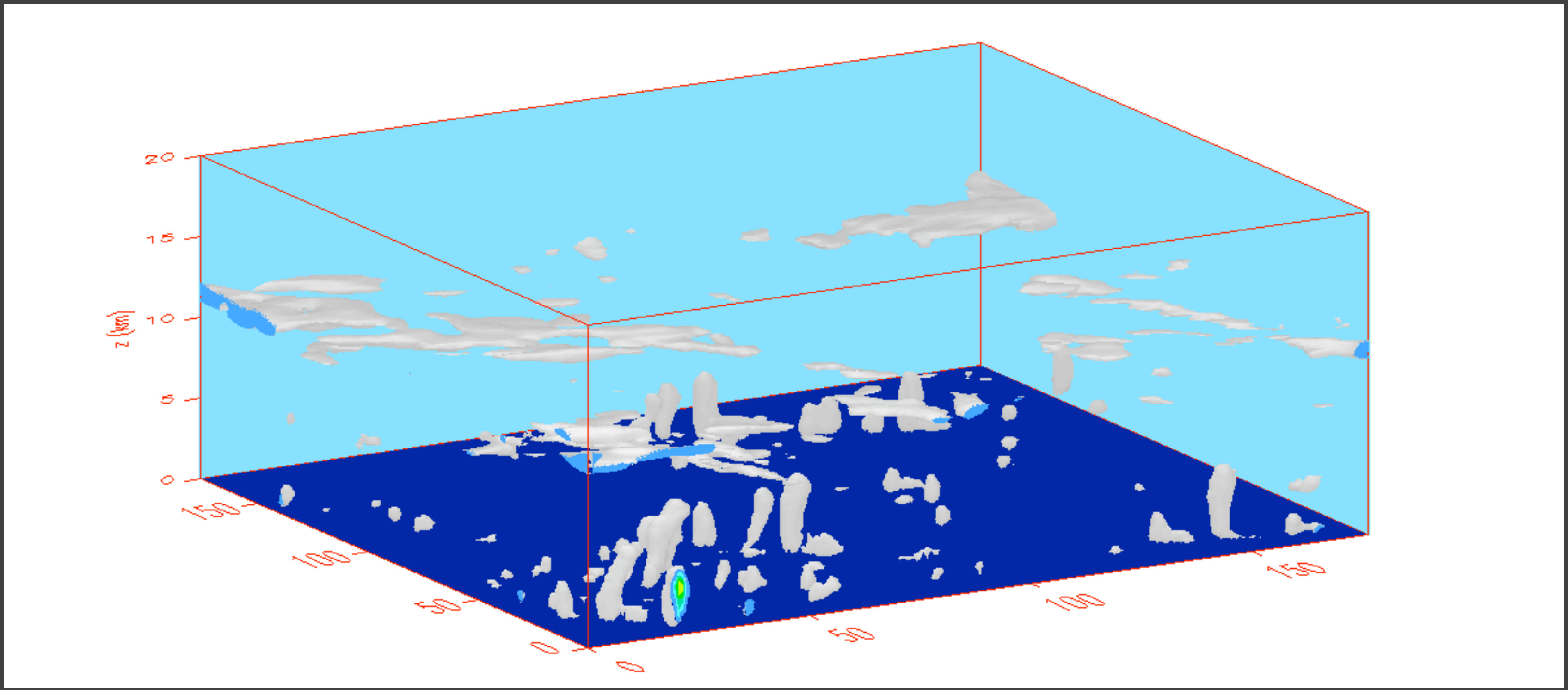
Simulations

- Simulations with different ice formation
    1. Diagnostic ice nuclei: $N_{ice}+N_{IN}= 30\ L^{-1}$
    2. Prognostic: ice nuclei consumed (nudged at 6 h time scale)
- Moderately strong monsoon event (19-20 Jan.)
- 20-hour simulations (after 36-hour spinup with bulk microphysics)
- Sampled every hour

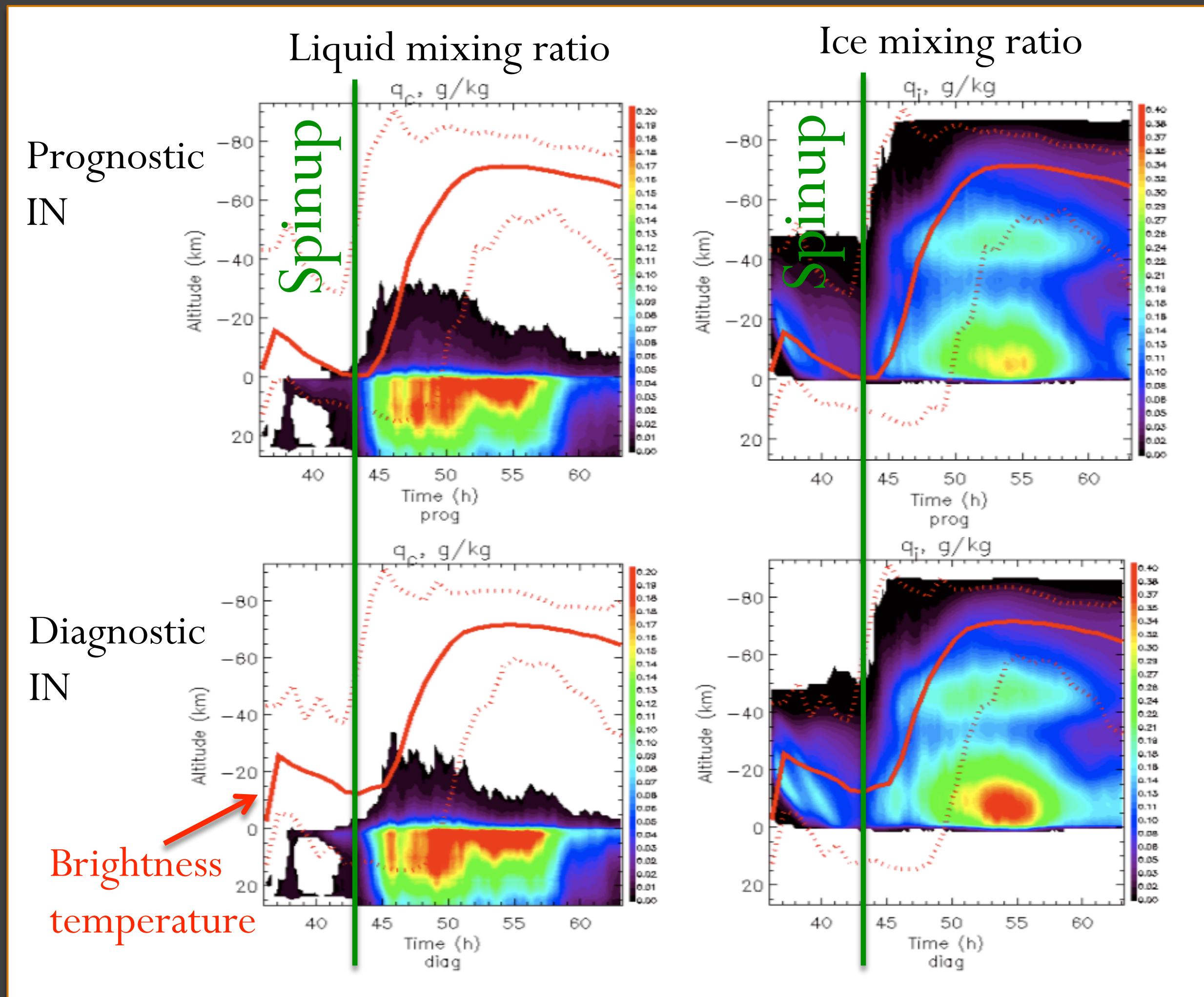


Model simulations

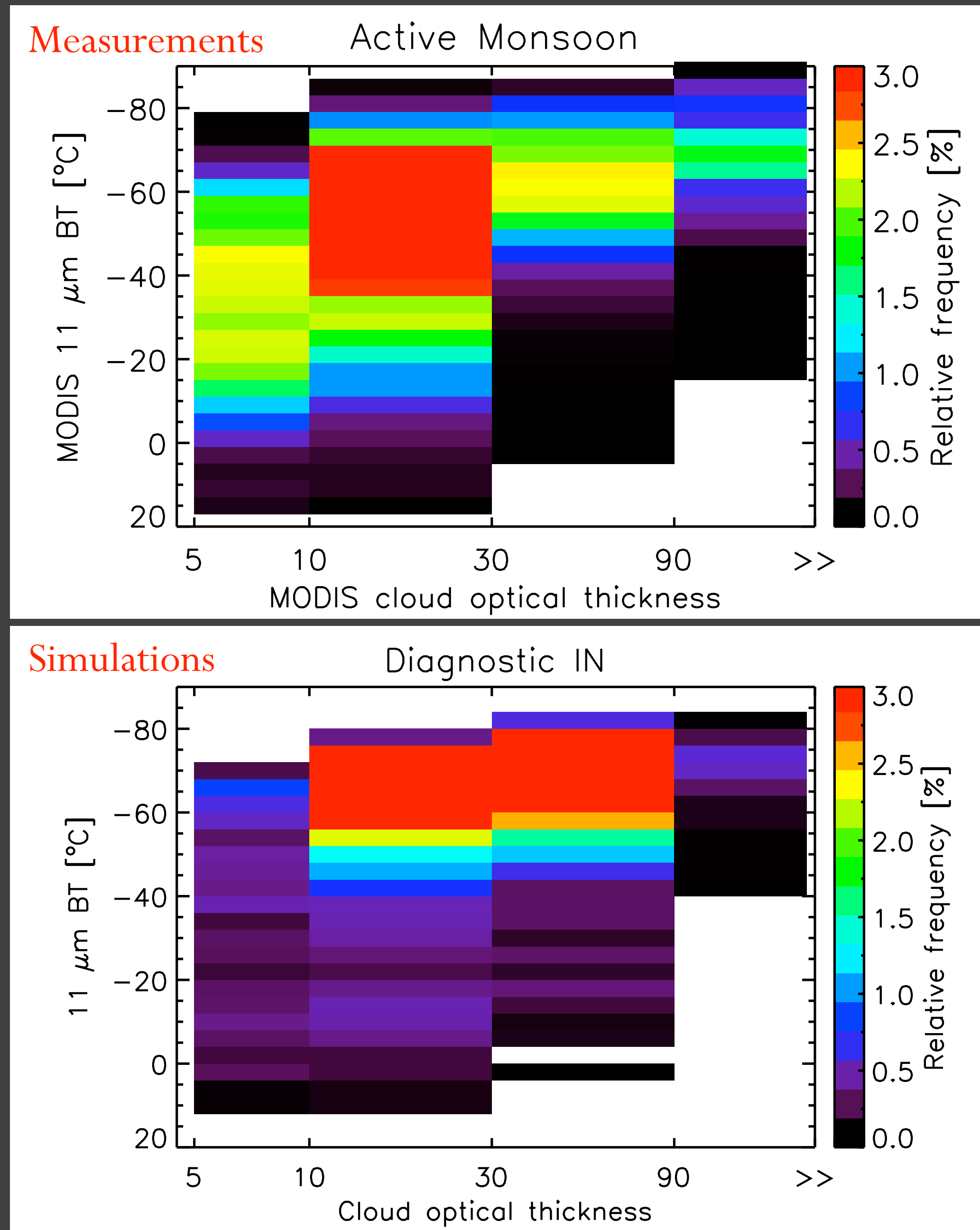
- Prognostic IN



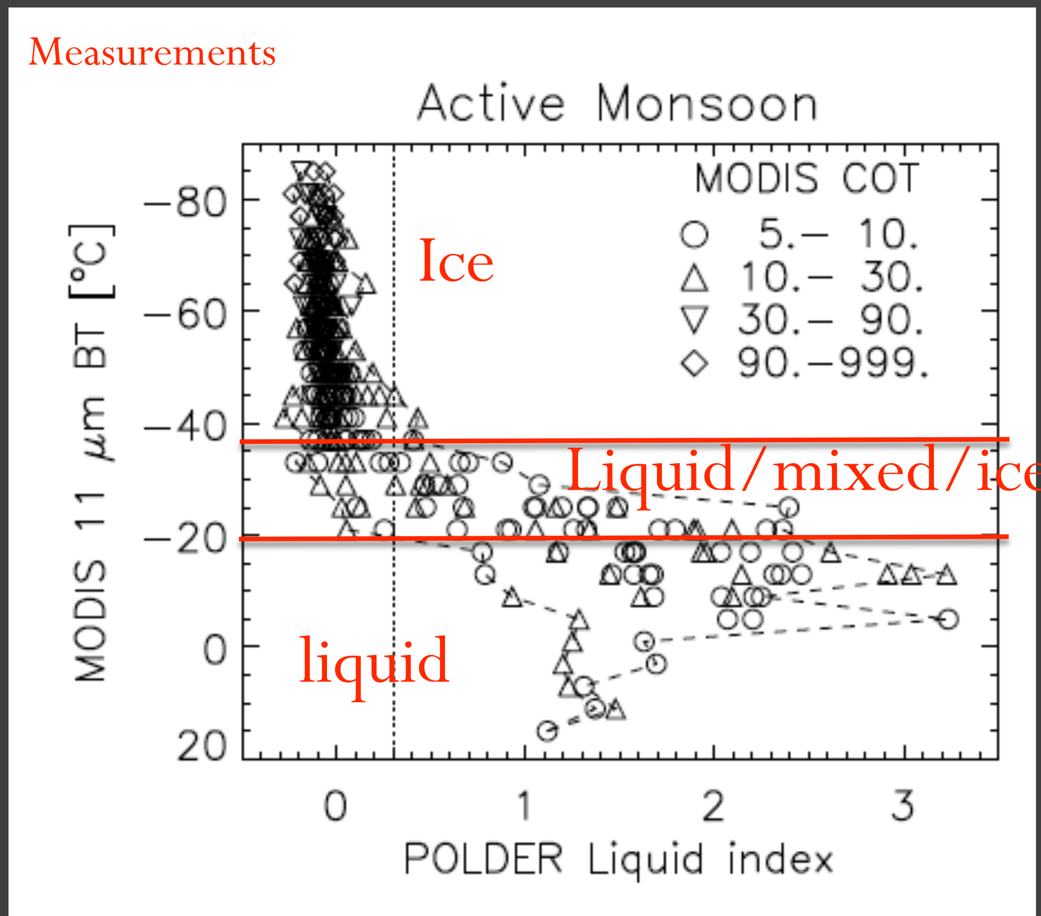
Domain averages vs time



Brightness temperatures and optical thickness

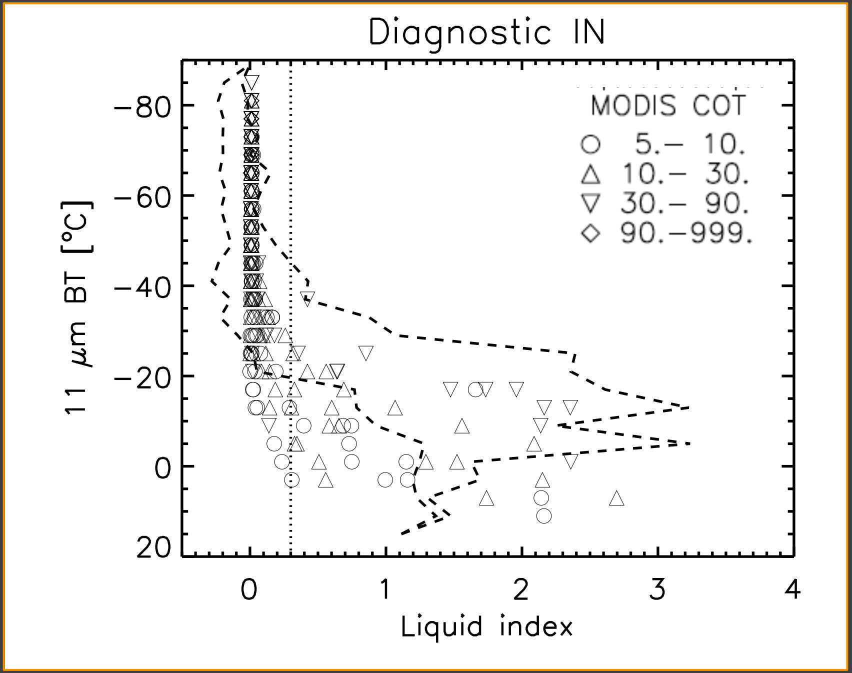


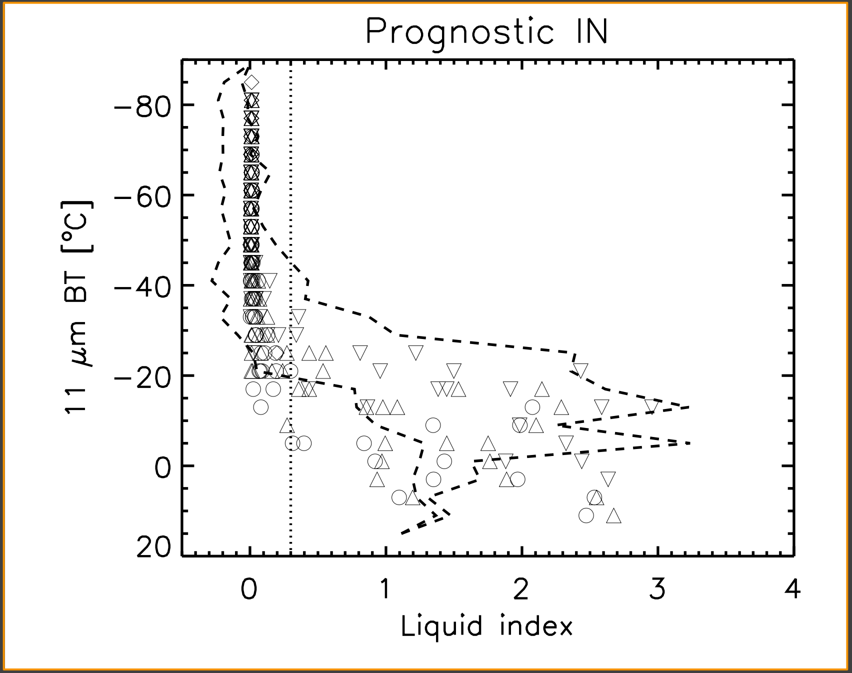
Liquid index for TWP-ICE active monsoon



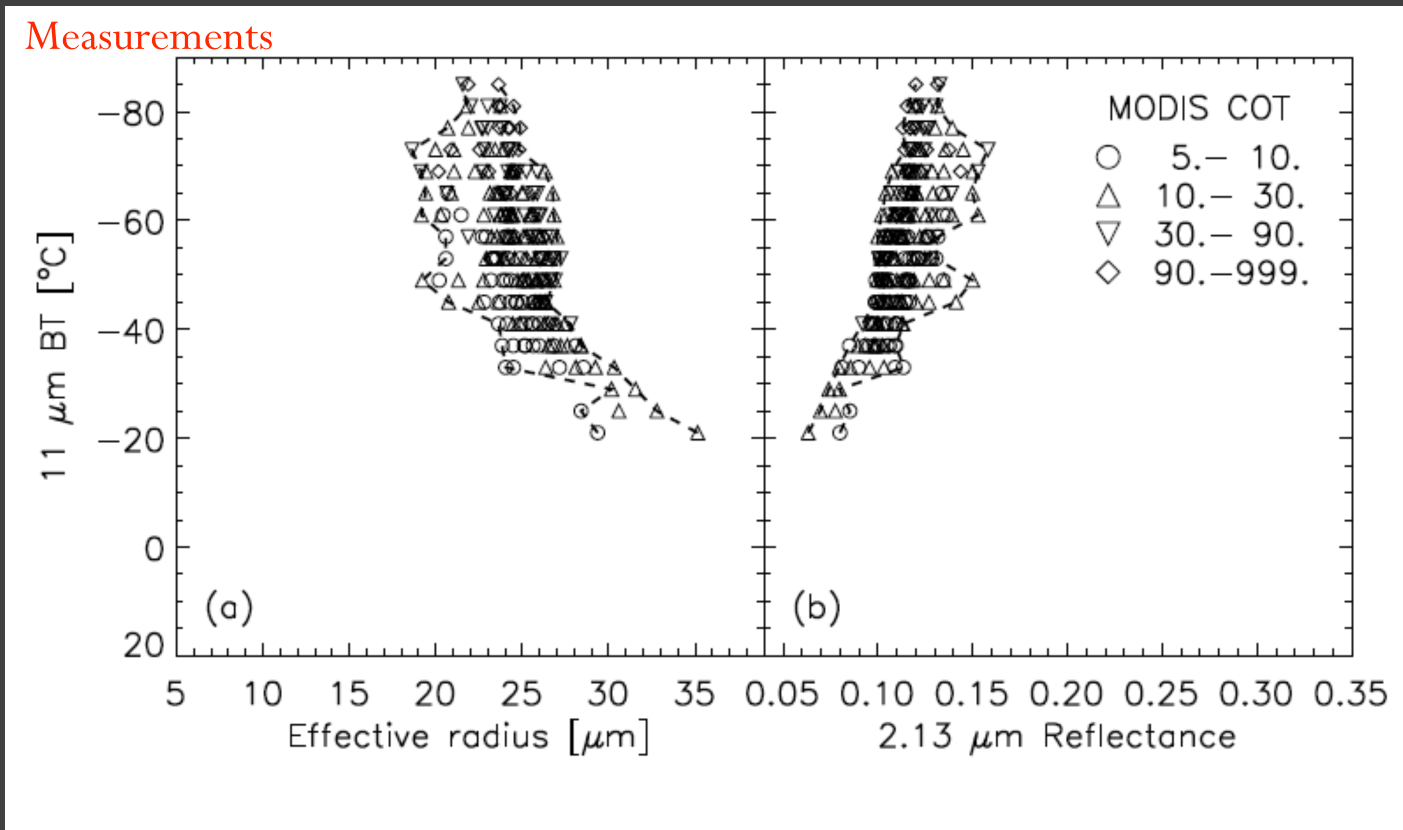
Simulated Liquid index

- Liquid indices simulated from model
- Using forward calculations of 0.86 μm polarized reflectances
- Too much ice at T > -20 C (spinup problems?)
- Super-cooled liquid at T~ -30 C





MODIS ice effective radius and 2.13 um reflectance



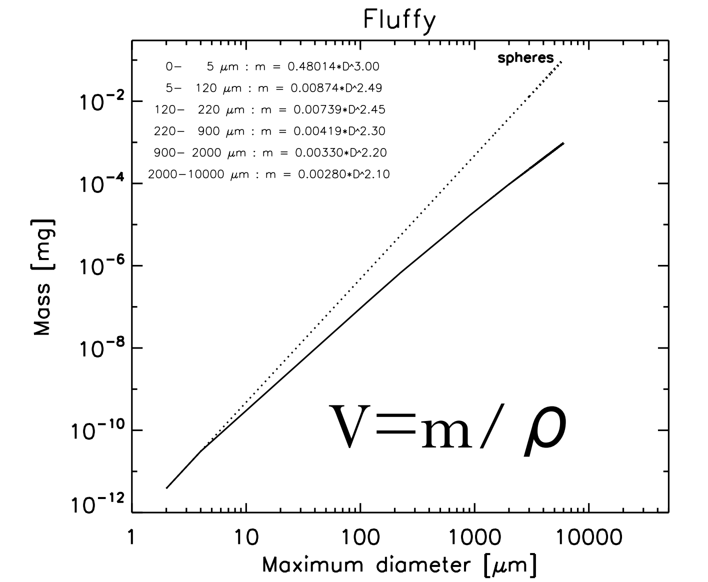
Evaluating modeled effective radius

- Definitions of ice effective radius vary
- Most models predict total ice mass, not effective radius
- Retrieval represents R_{eff} somewhere in cloud top, but where?
- Retrieval of effective radius depends on ice habit assumed
- R_{eff} of equal volume sphere >> R_{eff} real ice !

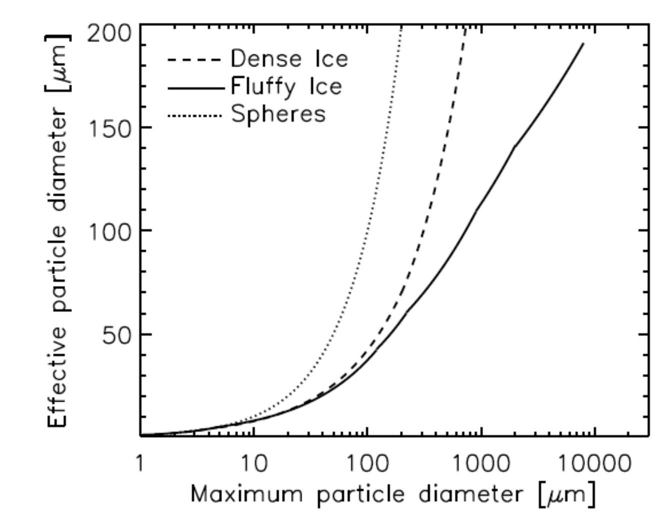
$$R_{eff} = \frac{3}{4} \frac{\int_0^\infty V(D) N(D)\, dD}{\int_0^\infty A_p(D) N(D)\, dD},$$

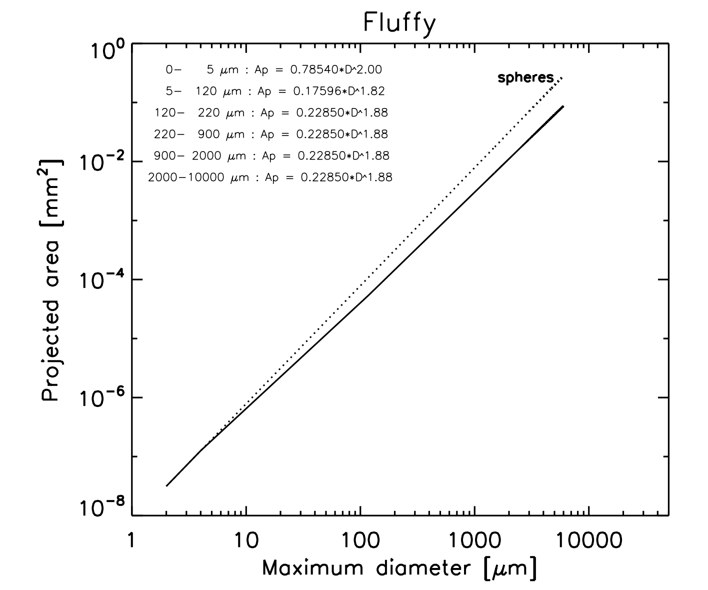
Calculation of effective radius from model

- DHARMA model uses 36 bins with specified
  - Maximum diameter
  - Mass
  - Area
- Same assumptions used for micro-physics and optical properties



$V = m/\rho$

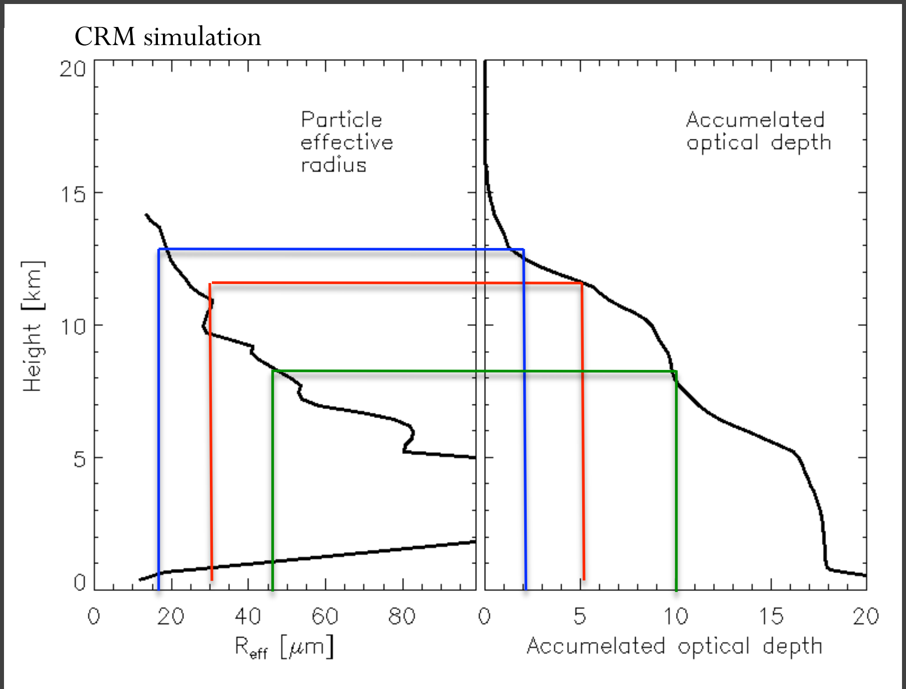




$D_{eff} = 3/2\ V/A$

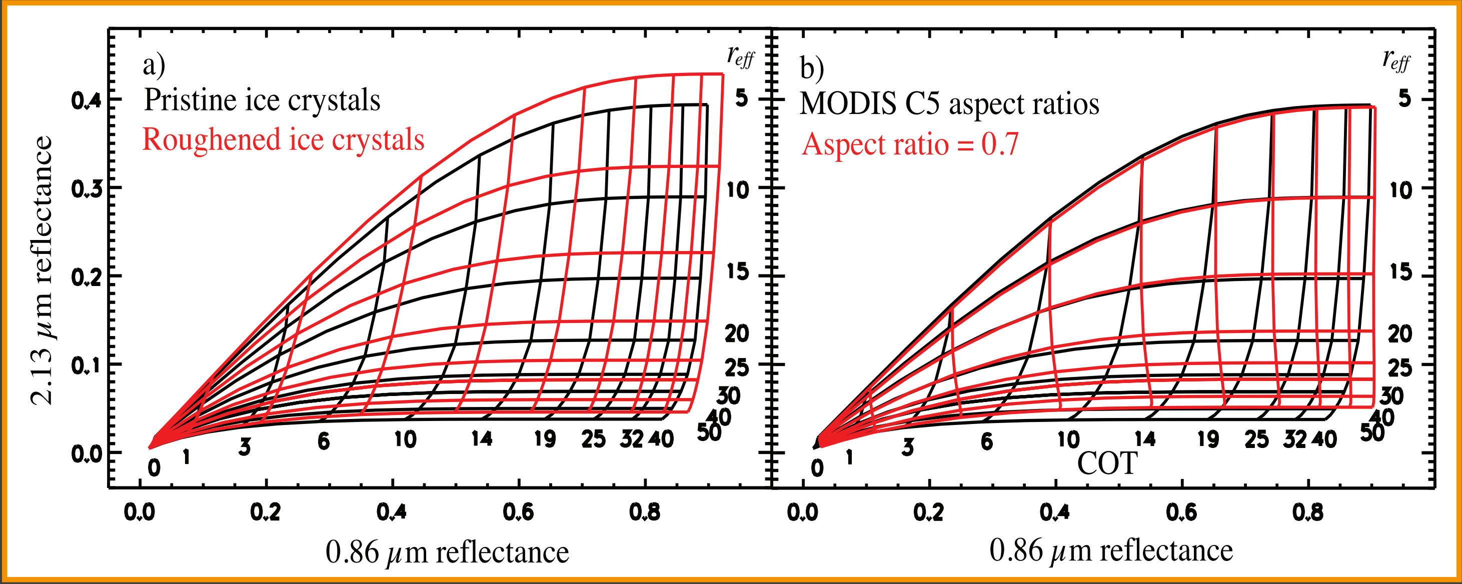
Calculation of effective radius from model

- Retrieval of ice R_{eff} represent the effective radii somewhere in the top of the cloud, but where?
- Past studies show retrieval is mostly sensitive to first 2 optical depths



Retrieval of effective radius depends on ice habit assumed

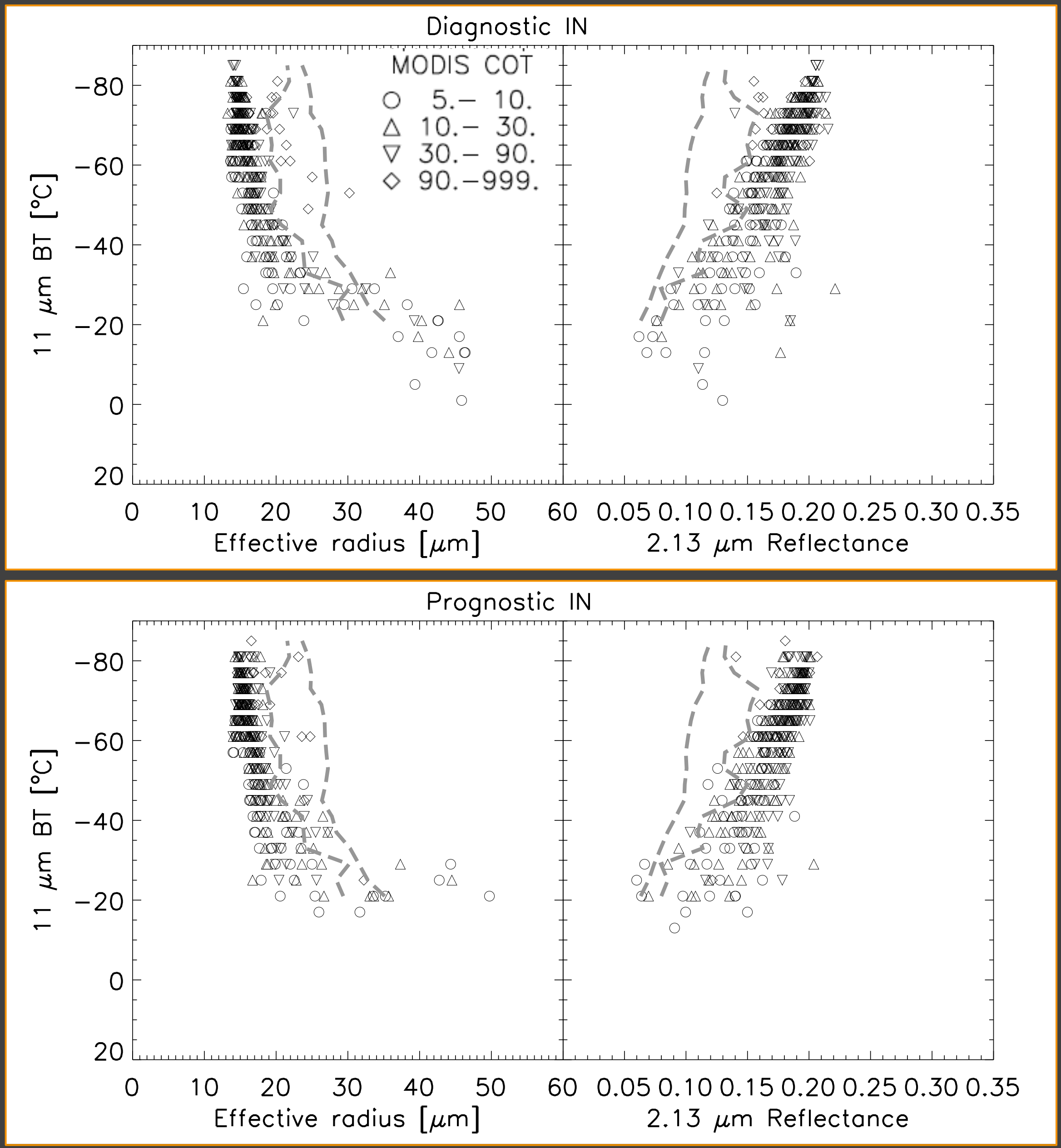
$$R_{eff} = \frac{3}{4} \frac{\int_0^\infty V(D)N(D)\, dD}{\int_0^\infty A_p(D)N(D)\, dD},$$



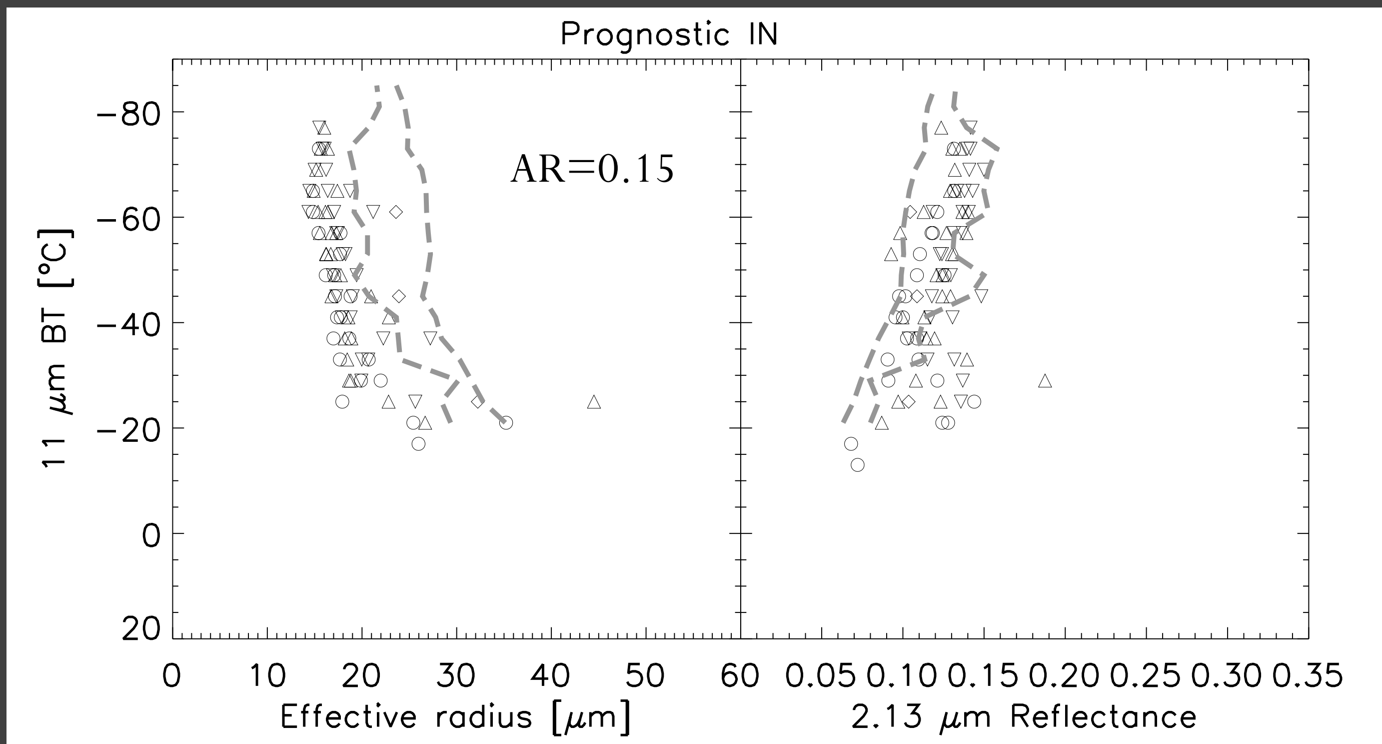
- Overcome problems by forward simulating 2.13 μm reflectance with known ice habit

Evaluation of model Reff

- R_{eff} integrated over first 2 optical depths
- Simulated 2.13 μm reflectances
  - AR=0.7
  - Roughness = 0.6
- Sizes not sensitive to IN treatment (homogeneous nucleation dominates?)



2.13 sensitivity to ice aspect ratio

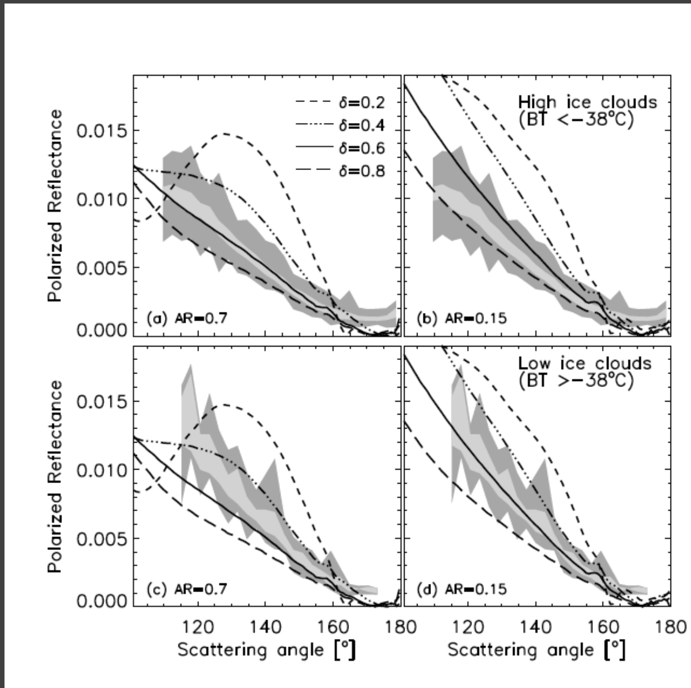


Conclusions measurements

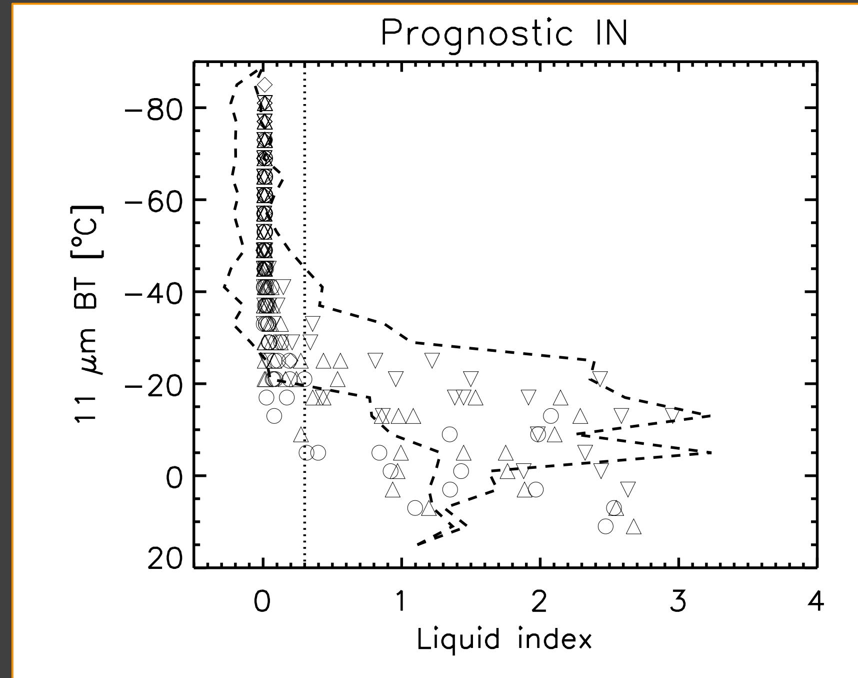
- Glaciation
  - Liquid at T > -20 C
  - Liquid/Mixed/Ice at -20 C > T > -35 C
  - Ice at T < -40 C
- Ice shapes
  - Compact rough crystals at T < -40 C
  - More extreme aspect ratios at T > -40 C
- Ice sizes
  - 18-28 μm at T < -40 C
  - 24-35 μm at T > -40 C

Conclusions model

- Model evaluated using forward calculations of
  - Brightness temperatures
  - 0.86 μm polarized reflectances
  - 2.13 μm reflectances
- Glaciation
  - Super-cooled liquid up to T~-30 C (similar to measurements)
  - Too much ice 0 C > T >-20 C (depending on IN treatment; spinup?)
- Ice sizes
  - R_{eff} 5-10 um too small
  - Sizes in cold tops not sensitive to IN treatment
  - Some too large ice in warm tops (Spinup?)
- Calculated R_{eff} and simulated 2.13 μm reflectances give similar results

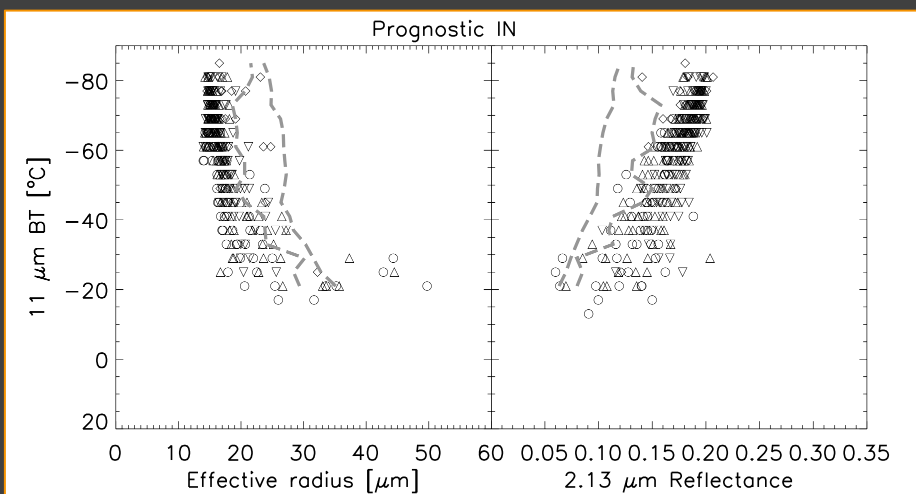


δ=0.2
δ=0.4
δ=0.6
δ=0.8
High ice clouds (BT <−38°C)
Low ice clouds (BT >−38°C)
(a) AR=0.7
(b) AR=0.15
(c) AR=0.7
(d) AR=0.15
Polarized Reflectance
Scattering angle [°]

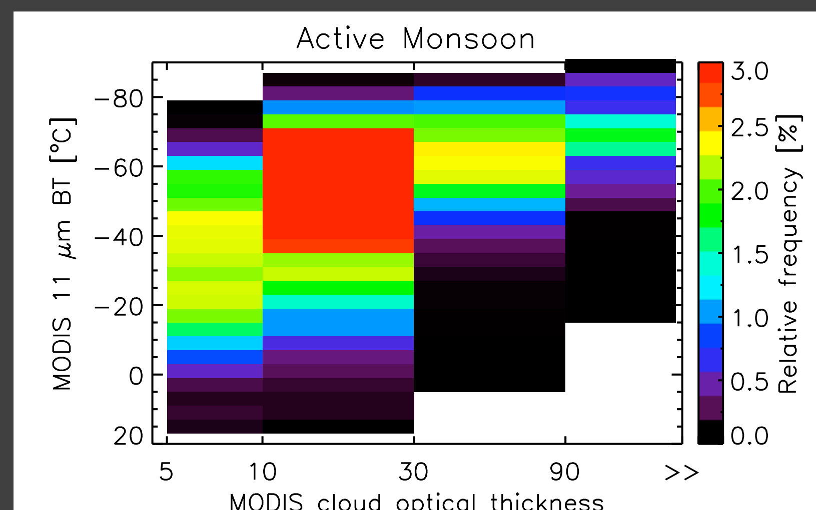


Prognostic IN
11 μm BT [°C]
Liquid index

End



Prognostic IN
11 μm BT [°C]
Effective radius [μm]
2.13 μm Reflectance



Active Monsoon
MODIS 11 μm BT [°C]
MODIS cloud optical thickness
Relative frequency [%]